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Building Integrated Concentrating Photovoltaics: A review

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ABSTRACT

For building integration, Concentrating Photovoltaic (CPV) systems can offer a host of advantages over conventional flat panel devices, the most notable being: a higher electrical conversion efficiency in the PV cells, better use of space, ease of recycling of constituent materials, and reduced use of toxic products involved in the PV cells' production process. However, the viability of Building-Integrated Concentrating PV (BICPV) systems is dependent on their ability to offer a comparative economic advantage over flat panel photovoltaic technologies whose market prices are decreasing from day to day and which offer other advantages such as ease of replacement of structural elements.

A comparative analysis is presented of the main existing CPV systems' suitability for use in buildings, in which the different challenges specific to integration of each system are discussed. The systems are categorized by type of concentration technology and concentration factor.

Contents

1. Introduction

At present, the use of solar concentrator systems is limited in scale and the majority of existing installations employ devices of considerable size; solar power towers, parabolic-trough concentrators, parabolic-dish concentrators and large Fresnel concentrators with two-axis tracking systems are clear examples. There are more than 30 companies developing Concentrating Photovoltaics (CPV); many are start-ups. Despite the current economical situation, there is a tendency for rapidly increasing production [1].

Producers of solar concentrators for small scale buildings-integrated installations must develop reliable systems which are adequate for their application. Single axis tracking designs are suitable for building integration. When comparing such a system with a flat panel PV device built for the same application, the additional cost of the tracker and its maintenance must be considered. Furthermore, flat panel systems may be used to replace structural elements in buildings, which in most cases is not possible for concentrating systems [2].

Buildings Integrated Concentrating Photovoltaics (BICPV) need to be designed in such a way which minimizes costs allowing them to compete with standard flat panel technology, the manufacturing costs of which are falling continually.

In addition to being technically and structurally sound, solar concentrators apt for architectural integration must fulfil the following requirements, these being a generalization of the criterion formulated by the IEA PVPS Task 7 workgroup for evaluation of the aesthetic quality of buildings integrated photovoltaics [3,4]:

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- Natural integration.
- Architecturally pleasing design.
- Good composition of colours and materials.
- Dimensions that fit the gridula, harmony and composition.
- Conformity to the context of the building.
- Well-engineered and innovative design.

BICPV systems may be installed either on the building façade or on the roof (which may be flat or sloped) producing in each case a different visual impact. Depending on the type of device, the system may be integrated in such a way that it is unseen, plays some role in the architectural aesthetic or that it constitutes in itself an architectural concept [2].

The integrability of a concentrator, being it reflective or refractive, depends on its concentration factor, C (defined as the ratio between the aperture area of the primary concentrator and the active cell area). Concentrating systems with $C > 2.5\times$ generally use a system to track the sun, whereas systems with $C < 2.5\times$ can be static. However, in the long term static concentrators with higher ratios which make use of luminescence and photonic crystals may appear [5]. Low concentrating ratio systems ($C < 10\times$) are of particular interest for as they are of linear geometry and thus one tracking axis is sufficient for efficient operation [6]. The combination of improved sheet metal capability with the PV industry's high capacity will offer a large deployment of low concentration PV [7].

Furthermore, CPV is a feasible method to reduce the high initial cost of PV solar energy. Concentrating solar radiation onto solar cells implies that the area of semiconductor devices is diminished; most being replaced by a cheaper element (the concentrator). Considering that a higher concentration factor results in higher cost reduction, it can be seen that within the concentration range where single axis tracking may be used, the most desirable concentration factor is that which approaches the upper limit of $10\times$.

The purpose of this paper is to review and analyze the CPV systems intended for incorporation in buildings according to the requirements enumerated above.

2. Critical review of concentration systems

The following is an analysis of the suitability for architectural integration of the principle types of existing concentrators, categorized by concentration factor.

2.1. High concentration systems ($C > 100\times$)

High Concentration systems require two-axis tracking with high precision (tolerances below 0.2°). The integrability of such a system will be highly compromised by the fact that it is mobile and by its size and dimensions which, even when minimized, are considerable. Incorporation is best achieved on the roof of the building (particularly for flat roofs) where the system is invisible from the exterior. This group is currently dominated by point focus Fresnel systems (Fig. 1).

There are a number of companies producing high concentration systems, some of whom shall now be mentioned:

Sol3g, now absorbed by Abengoa Solar, produce a modular system with a row of 10 Fresnel lenses per module (solar aperture 1200 mm × 120 mm) which may be custom designed according to space and consumption requirements [8]. The array of modules is positioned on a high precision tracker fabricated by Feina Ltd. [9]. Green and Gold Energy offer a system called SunCube™ which consists of a device of approximately 1 m^2 (1064 mm × 1064 mm) aperture formed of nine Fresnel lenses divided into three rows. Each system is coupled to a small two-axis tracker [10]. Soliant Energy have commercialized a system formed of 6 modules on a single tracker (SE-500×). Each module is consists of 8 Fresnel lenses in two lines of 4. The dimensions of each module are 708.02 mm × 377.82 mm [11]. Using similar designs to those previously mentioned and employing Fresnel lenses, Sunrgi have designed the Xtreme Concentrated Photovoltaics™ (XCPV) system [12] and Whitfield Solar the WS-Si24 system. The latter has a concentration factor of $70\times$ and therefore is a medium concentration system [13]. However, the optical and tracking technology used imply characteristics of integration that place it within this section.

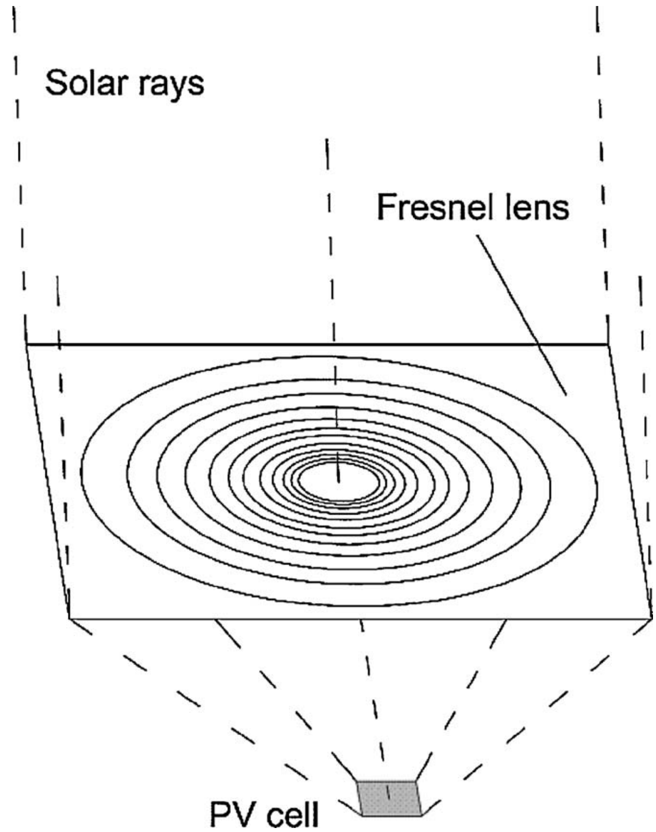

Fig. 1. Schematic of an Aspheric Fresnel lens.

Using point concentration reflectors, Menova have developed PowerSpar [14], and SVV Technology Innovations a Ring Array Concentrator (RAC), which emulates an aspherical point focus lens using reflectors [15,16].

In addition to the above systems, it is worth mentioning the concentrator based on Cassegrain Optics (Fig. 2) which has been commercialized by SolFocus [17–19] and the Light-guide Solar Optics (LSO) system presented by Morgan Solar Inc. [20], which is based on optical light guides (Fig. 3). As with the systems described in the previous paragraph, these can be installed on flat roofs. Both have a minimal receiver size, encapsulating the PV cells within the concentrator itself.

Given that the practical degree of integration of high concentration systems is limited by the need to incorporate them onto a high precision two-axis tracker, their means of integration are analogous between each case. It is therefore considered that the architectural issues are already well explained.

2.2. Medium concentration systems ($10\times < C < 100\times$)

Medium concentration systems can generally be divided into two groups: parabolic troughs and those using Fresnel optics in the form of lenses or mirrors. Concentrators which achieve the higher end of this concentration range (60–85×) and which, due to their size, make integration in buildings impossible are the Concentrat-

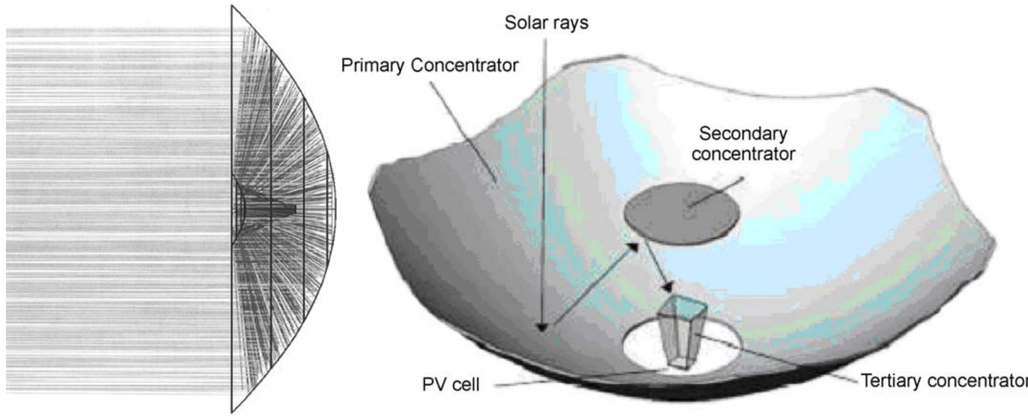

Fig. 2. Schematic of the Cassegrain concentrator. In the left, 2D ray tracing view and in the right, 3D model of the system [17].

ing Solar Power (CSP) devices. In this type of systems, when decreasing the concentration ratio, building integration is facilitated.

An important problem associated with linear CPVs is overheating produced by the high density of light flux received by the cells, the majority of which is transformed into heat. The high concentration systems mentioned in the previous section used a passive cooling system, facilitated by the reduced dimensions of the cell which allow the use of a fin based heat sink. Contrarily, in the case of linear concentration systems, passive cooling is complicated due to the larger surface area of the solar cells. This results in less cost effective dissipators than in the case of insulated cells [21]. For solar receivers which receive linearly concentrated light, the most adapt means of cooling is by active dissipation using liquids such as heat conducting fluids [22]. A new group of solar generators has appeared which take advantage of the evacuated heat stored in the thermal fluid as a bi-product. These are known as hybrid or co-generation Photovoltaic Thermal Concentrators (CPVT) [23–30].

Medium concentration systems present a wide range of possible building integration configurations. The principle designs, grouped by their integration characteristics, are described below:

2.2.1. Parabolic trough concentrators

The installation of parabolic trough concentrators in buildings is similar to that of high concentration systems; they are generally placed on flat roofs and are ideally hidden from view. Solar tracking is achieved by rotation of the entire concentrator/receiver ensemble about a single axis. The majority of devices which use parabolic concentrators are thermal generators [31]. Exponents of parabolic CPV systems are: The Solar 8 system [32] commercialized by companies Arontis Solar and Absolicon Solar Concentrator, which concentrates with a ratio of 10× onto a Photovoltaic Thermal (PVT) receiver of bifacial cells actively refrigerated using a fluid. The Combined Heat and Power Solar System (CHAPS) developed at the Australian National University, with a concentration factor of 37×, which also employs a PVT module [26]. The Euclides system designed at the Polytechnic University of Madrid, with a concentration factor of 38.2×, in which the cells are passively refrigerated using fins [33,34]. In 2009, Niedermever patented a new concentrating system for PVT generation [35].

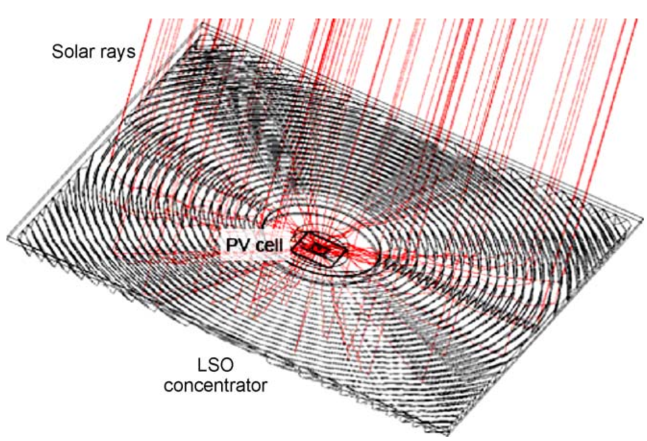

Fig. 3. Light-guide Solar Optics (LSO) system presented by Morgan Solar Inc. [20].

2.2.2. Linear Fresnel reflectors

In the case of parabolic troughs, daily solar tracking is achieved by moving the entire concentrator/receiver ensemble. However, within this range of concentrations good versatility is offered by systems which work using Fresnel reflection, some of which are worthy of note (some of the systems described below are included due to their importance as concentrating technologies, despite being thermal collectors):

(1) Concentrators with two-axis trackers in which tracking is achieved by movement of the entire system, such as the BiFres system developed at the University of Lleida (equipped with a PVT receiver), whose integration in buildings would be restricted to flat (horizontal) roofs [25] (Fig. 4).
(2) Static concentrators in which solar tracking is achieved by movement of the receiver. This option offers greater scope for integration in buildings as it may be easily installed on either flat or inclined roofs. Installation on façades however presents certain problems: the mirrors prevent light from passing into the building and the mobile receiver must protrude outward from the building creating strain on the building structure and an anaesthetic appearance. The main exponent of this technology is the CCStaR system developed at the University of the Balearic Islands (equipped with a thermal receiver). It should be mentioned that in the most recently presented CCStaR prototypes the Fresnel reflectors are replaced by parabolic reflectors [36].
(3) Concentrators in which the tracking is achieved by the movement of the individual mirrors. The possibilities for integrating such systems are similar to those for the previous case of a stationary concentrator. The most important design within this group is the Compact Linear Fresnel Reflector (CLFR) presented in 1997 by Mills and Morrison [37] and commercialized by Ausra. The CLFR system is used for the direct steam generation. Similar systems to the CLFR have been developed, these being the solar collector Solarmundo presented by

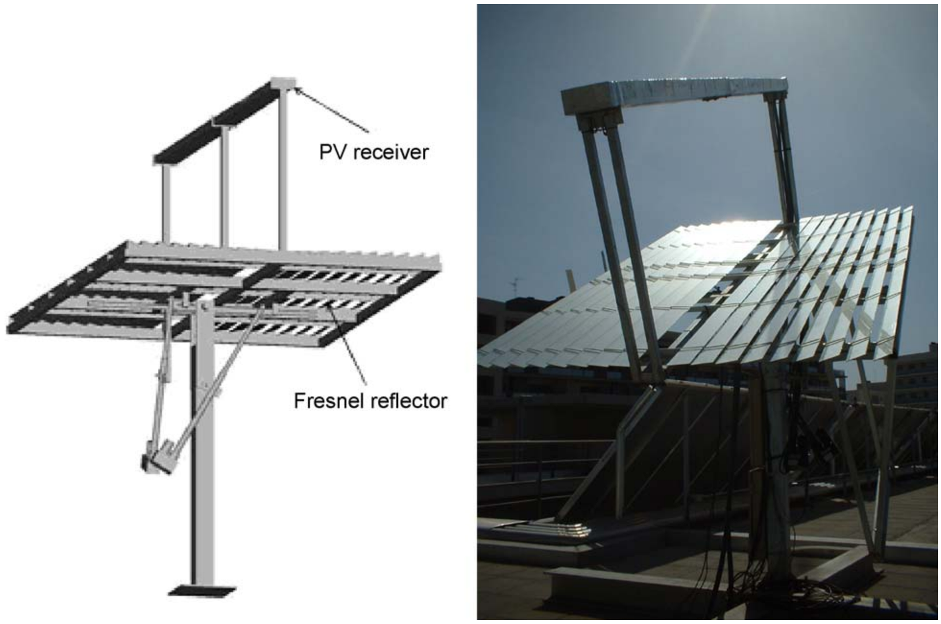

Fig. 4. Two-axis Bifres Fresnel reflector [25]. The PV receiver is water cooled, getting benefit of the thermal energy (PVT module).

Häberle et al. in 2001 [38] and commercialized by Power Group GMBH and the Mirroxx Fresnel collector commercialized by Mirroxx GMBH, a spin-off of PSE-AG- [39]. Using the same concentration principle, the company HelioDynamics have presented a collector, HD211, for integration in buildings with a receiver which can be thermal or PVT (currently the HD211, renamed to HD10, only incorporates a thermal receiver) [40]. The University of Lleida has constructed another such system with a PVT receiver in 2009 in collaboration with *NUFRI* Corporation and Trigen Solar S.L.

A new concept in the field of Fresnel reflection systems is the so-called Non-imaging Reflective Lens (NIRL) concentrator, of which there are two types: the axially symmetric Ring Array Concentrator (RAC) and the linearly symmetric Slat Array Concentrator (SAC) [41]. These operate by using mirrors to direct and concentrate light onto a receiver behind the optical element thus emulating a lens (Fig. 5). The high concentration, RAC, requires two-axis tracking, whereas the medium concentration SAC can be employed with either one- or two-axis tracking [42]. This type of concentrator combines the high optical efficiency achievable by mirrors with the flexibility of design which is characteristic of lenses. The principle drawback of these systems is that solar tracking is achieved by the movement of the whole system, incurring the aforementioned restrictions with regard to architectural integration.

The University of Lleida is currently developing concentration technology which uses reflection, in a similar way to the systems developed by Chemisana and Rosell [43], but with a design which prioritizes architectural integrability. The system consists of a linear Fresnel reflector which focuses radiation in a manner analogous to a lens. The receiver remains static and solar tracking is achieved by a simple and effective way by rotation of the individual mirrors. Thus overall movement is minimized facilitating incorporation into buildings and offering different possibilities for suiting the varied requirements of specific installations (Fig. 6).

High and medium concentration reflective systems are summarized in Table 2.

2.2.3. Linear Fresnel lenses

Firstly, before commenting on the different properties and characteristics of Fresnel lenses when applied to BICPV, two systems must be mentioned. Although of low architectural integrability, as the systems described previously, are the first references of this kind of linear concentrators.

These products are both formed by arched Fresnel lenses situated on a solar tracker. The first, designed by Entech Solar (USA)

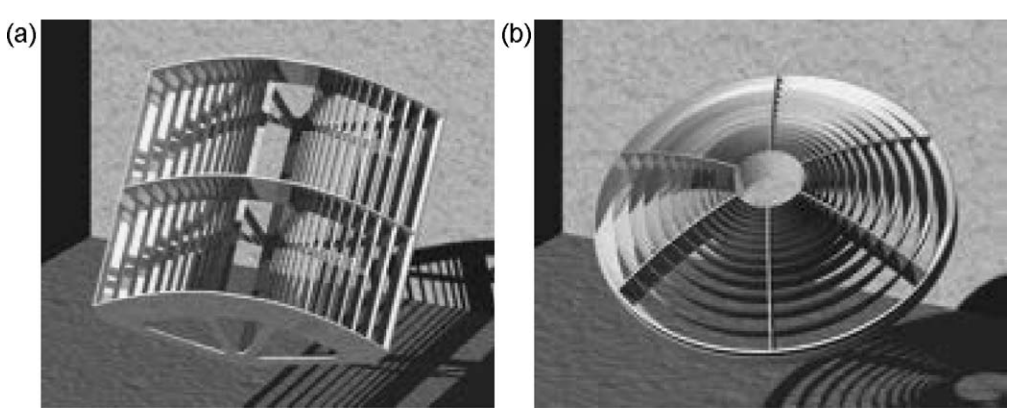

Fig. 5. (a) Ring Array Concentrator (RAC) and (b) Slat Array Concentrator (SAC) [16,41].

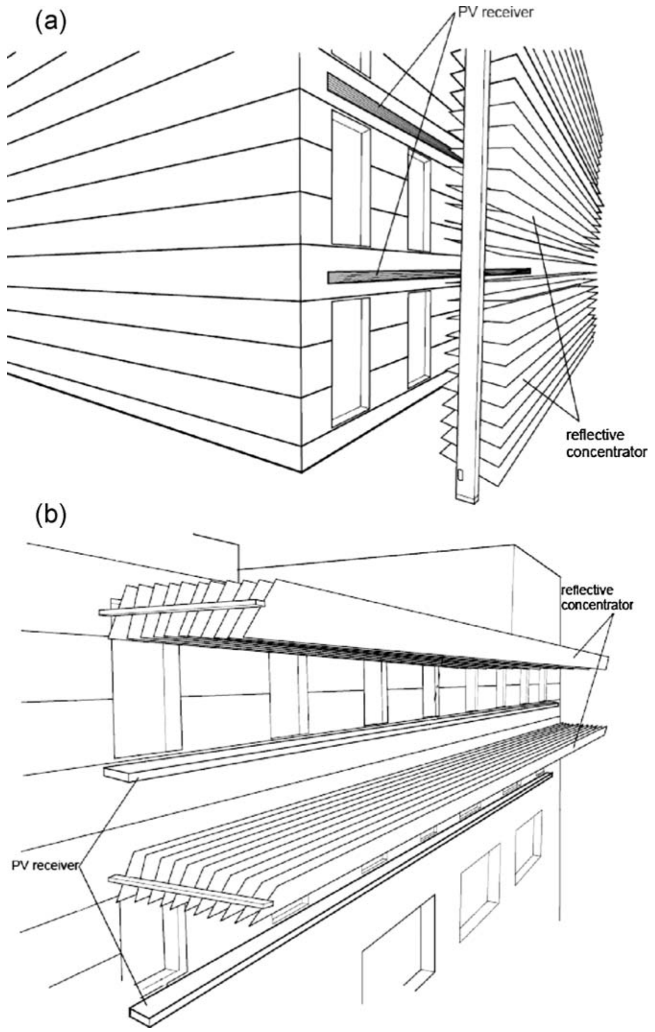

Fig. 6. Building integrated system presented by Chemisana and Rosell [43], (a) Curtain wall architectural design and (b) Parasol architectural design.

[44], uses a two-axis tracker and a PV or PVT receiver. The second, designed by SEA Corp. (later Photovoltaics International) [45,46] uses a one-axis tracker and a PVT receiver. Recently, Entech Solar has announced two new systems; TermaVolt™ II (PVT) and SolarVolt™ II (PV). Both systems are based on the same technology but using different receivers. Entech has resized the initial prototypes designed in the 80 s into these two smaller and low-cost devices applicable for both ground and roof-mount applications.

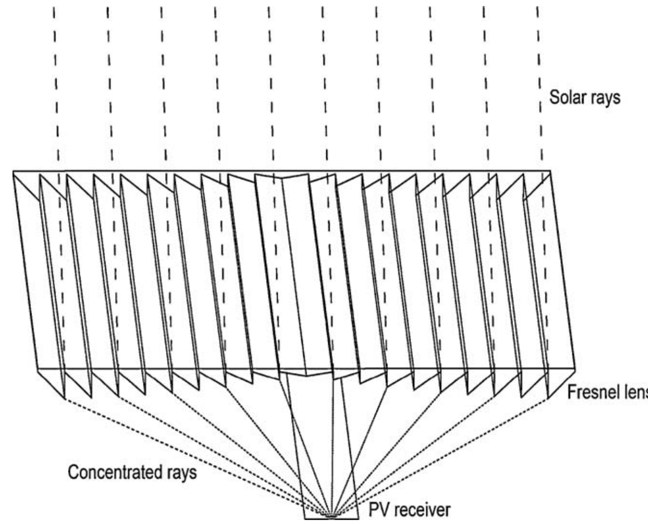

Fig. 7. Schematic of a linear Fresnel lens.

Linear Fresnel lenses (Fig. 7) have a number of attractive features when used for solar concentration applications: they may be produced in large sizes; their aspect ratio can be designed to be small, leading to a compact concentrating system; they may be very thin, minimizing the cost of optical material and reducing the mechanical load on the supporting structure; and they may be made of reliable and durable material [47]. The ability of linear Fresnel lenses to separate the beam from the diffuse solar radiation makes them useful for illumination control in the building interior space. The Fresnel lenses are advantageous because they can combine within them both the concentrating element and the optically transparent window. The use of Fresnel lenses as a transparent covering material for lighting and energy control of internal spaces has attracted special attention recently [48].

In addition to mentioning the general benefits of Fresnel lenses, some comparison should be made between those which are image forming and those which are anidolic. Image forming Fresnel lenses for solar applications require high precision tracking. Non-imaging lenses, often convex and arched in shape and designed for medium concentration using one-axis tracking, have been devised as highly competitive solar collectors. If the tracking requirements are minimized, the cost reduction achieved by reduction of the PV cells' surface area outweighs the cost of the optical elements [49,50].

Table 1
Concentrating systems which use Puntual Reflectors (PR), Parabolic Trough Reflectors (PTR), Linear Fresnel Reflectors (LFR) as a primary concentrator.

Company or reference	Actual status of the system	PR/PTR/LFR	C[a]	Cell type
Menova Energy [14]	Commercially available	PR	1450	3J[b]
SVV Technology Innovations (RAC) [15,16]	Commercially available (only concentrator provided)	PR	2500×	3J
Solfocus [17–19]	Commercially available	PR	500×	3J
Aronstis Solar [32]	Commercially available	PTR	10×	c-Si[c]
Euclides system [33,34]	Demonstration and test installations	PTR	37×	c-Si
CHAPS system [26]	Demonstration and test installations	PTR	38.2×	c-SI
BiFres system [25]	Demonstration and test installations	LFR	11×	c-Si
HelioDynamics [40]	Commercially available (currently only thermal module)	LFR	10×	p-Si[d]
Trigen Solar	Demonstration and test installations	LFR	20×	c-Si
SVV Technology Innovations (RAC) [15,16]	Commercially available (only concentrator provided)	LFR	40×	c-Si
Chemisana and Rosell [43]	Demonstration and test installations	LFR	18×	c-Si

[a] C: geometric concentration ratio.
[b] 3J: triple-junction solar cell.
[c] c-Si: crystalline silicon solar cell.
[d] p-Si: polycrystalline silicon solar cell.

Table 2
Concentrating systems which use aspheric/Puntual Fresnel Lenses (PFL) or Linear Fresnel Lenses (LFL) as a primary concentrator.

Company or reference	Actual status of the system	PFL/LFL	C[a]	Cell type
Abengoa Solar [8]	Commercially available	PFL	476×	3J[b]
Green and Gold Energy [10]	Commercially available	PFL	1370×	3J
Soliant Energy [11]	Commercially available	PFL	500×	3J
Sunrgi [12]	Commercially available	PFL	1600×	3J
Whitfield Solar [13]	Commercially available	PFL	70×	c-Si[c]
Photovoltaics International [45]	Stopped production in 2000	LFL	10×	c-Si
Entech Solar [44]	Commercially available	LFL	20×	c-Si
Chemisana et al. [47,54]	Demonstration and test installations	LFL	30×	c-Si

[a] C: geometric concentration ratio.
[b] 3J: triple-junction solar cell.
[c] c-Si: monocrystalline silicon solar cell.

The concept of using a fixed concentrator with a tracking absorber has been mentioned in the past [51–53]. It is based on a stationary wide angle optical concentrator that, whatever the location of the sun, transmits the input radiation onto a small moving focal area, which, in turn, is tracked by the PV receiver. Following this approach, the University of Lleida has developed a prototype based on a stationary Fresnel lens which focuses solar radiation onto a PVT receiver which tracks the moving focal area [54]. The advantages of this type of CPV make it architecturally versatile, allowing integration onto flat or inclined roofs or as lightweight façades, windows, etc. Thus their characteristics correspond perfectly to the requirements of well integrated systems described by the IEA PVPS Task 7 workgroup [3,4].

Refractive systems under high and medium concentration ratios are summarized in Table 1.

2.3. Low concentration systems ($C < 10\times$)

Within this group fall an extremely large number of systems and variations based on very distinct technologies.

From an intuitive point of view, the simplest system is the V-trough reflector which directs light onto the receiver using flat mirrors [55–59]. The V-trough can achieve at most 3× concentration. To ensure uniform illumination of the PV cells, planar reflectors require solar tracking [60–66]. If solar tracking is not continuous, the V-trough behaves as an anidolic (non-imaging) optical system. Use of such devices, as with all low concentration systems, is beneficial as commercial cells may be used and as cell heating is reduced [67,68]. However, despite the low light flux, cells may overheat to temperatures above 80 °C. Operation is considerably improved through use of a thermal dissipator [69]. By taking advantage of the extracted heat, such a system can be converted into a PVT generator.

Compound Parabolic Concentrators (CPC) form a category of reflectors largely used for static systems. When used to illuminate PV cells, high losses are suffered due to the non-uniform illumination pattern produced on the cell surface. V-trough systems are less prone or producing detrimental hot-spots than are CPC systems [70]. Many works can be mentioned within this category [71–81]. With the objective of improving the system, many authors have opted for incorporation of bi-facial cells [82–88]. These double the amount of radiation or concentration that can be realized at the PV receiver. However, their use is not possible in high concentration systems as they have no un-illuminated surface onto which the essential heat dissipator may be attached. Designs of static concentration systems (with a typical acceptance angle of 30°) are normally intended for use with bifacial cells. Their concentration factor may be increased by use of a dielectric [89]. Some examples of static concentrators which use dielectrics are presented in [90]. The cells positioned in a V-trough concentrator filled with oil or water (the dielectric) which also serves a cooling function. The designed presented in [91] uses an anidolic lens to reach a concentration factor of 2× and optical efficiency of 94%. The flat static concentrator described in [92–95] has been used to analyse various possible configurations including use of monofacial cells (1.5×) or bifacial cells (2×) and different types of illumination of the rear face. However, Uematsu et al. have not taken into account thermal effects in the PV cells.

Two linear dielectric non-imaging concentrating designs (symmetric and asymmetric) for PV integrated building façades were analyzed using 3D-ray tracing analysis [96]. A "slim line" design was reported to achieve a concentration ratio of 4× [97]. Thermal analysis indicated that performance loss through additional heating of the PV cells was more than offset by the gains achieved through concentration. The efficiency of the module was reported to be 15% greater than that of the flat plate module. Static concentrators offer a compromise between high concentration systems that require tracking and one-sun flat plate modules [97].

Systems which concentrate radiation using elements opaque to visible light (CPC, V-trough) cannot be installed on areas of a building through which light is supposed to enter without reducing natural lighting in the interior. To reach a certain concentration factor, the reflecting surface area used by these systems is elevated compared to the surface area of PV cells. Given the detrimental effect this has on illumination of interior spaces, low concentration static concentrators are preferable for architectural integration. These form the vast majority of CPC systems. They may be designed to be installed at any inclination or position which receives solar radiation (flat roofs, inclined roofs, façades, etc). What is more, although the reflector area is high with respect to the PV cell area, the volume of the entire system is relatively reduced, the geometry approximately tending to a parallelepiped.

The previously mentioned linear Fresnel systems with one-axis tracking [45,46] can also be included within the low concentration group. Leutz et al. [49] designed a convex shaped nonimaging stationary Fresnel lens (1.5–2×) intended for warming up evacuated tubes, but able to be used with PV including secondary optics.

Other low concentration systems which are currently less used but are the subject of some study are: Fluorescent/Luminescent Concentrators, Quantum Dot Concentrators and Holographic Concentrators.

The idea of using Fluorescent Concentrators (Fig. 8) to concentrate both direct and diffuse radiations without tracking systems first appeared in the late seventies [98,99]. In a fluorescent concentrator, a matrix of dye molecules absorbs radiation and emits light with a longer wavelength. Most of the emitted light is internally totally reflected and therefore trapped and guided to the edges of the concentrator, where solar cells convert it into electricity. This concept was investigated intensively in the early 1980s [100,101]. After 20 years of progress in the development of

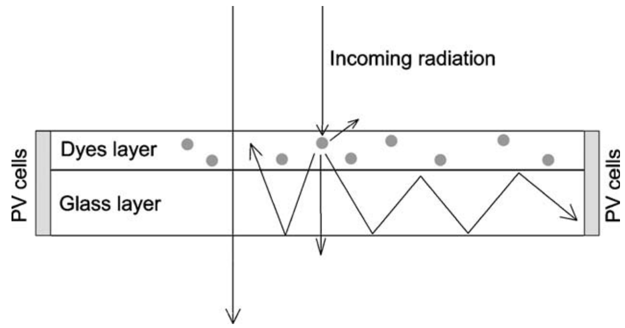

Fig. 8. Fluorescent technology. The main part of reemitted photons are trapped in the layers and guided by total internal reflection to the PV cells placed on the edges. Photon loss occurs because of nontrapped emission or absorption by other dyes. Radiation frequencies noncaptured by the dyes are transmitted through the layers and can be captured and collected by a second fluorescent device or other system which take benefit of them.

solar cells, fluorescent dyes and new concepts, several groups [102–110] are currently reinvestigating the potential of fluorescent concentrators. In the quantum dot concentrator, the luminescent dye is replaced by quantum dots. Quantum dots are crystalline semiconductors which degrade less than organic dyes. Quantum dots can be tuned to the absorption threshold by the choice of dot diameter. Red shift between absorption and luminescence is primarily determined by the variance of dot sizes, which in turn can be optimized by choice of growth conditions. Reabsorption can therefore be minimized and high efficiencies and high concentration ratios achieved [111]. Of the systems which use this kind of technology, the organic dye based Organic Solar Concentrator (OSC) designed in the Massachusetts Institute of Technology (MIT) and commercialized by Covalent Solar has had the most impact, particularly within the field of building integration. The primary advantages of this system are that it does not require tracking and that its geometry is completely planar. It is formed of a stack, the principle layers being the OSC and the PV cells. This system is aesthetically superior to conventional PV systems; the colour is tuneable, better views through, transparent metal oxide contacts are not required and they may be formed with flexible plastics. Due to their versatility, their position in buildings varies from atriums and roofs to windows. The concentration for which the system works with best efficiency, when combined with a variety of PV cell types, is 3 suns [112].

The idea of holographic solar concentrators was first proposed in the early 1980s [113–117]. Holographic elements have a number of advantages over conventional optical elements; they are lightweight, easy to reproduce and one holographic element can be used to perform several different functions. For example, there is a demonstration project which utilizes light-directing holograms for both daylighting and PV power generation [118]. Holograms can be fabricated which concentrate the spectrally disperse solar radiation [119].

There has been a surge of interest in this kind of technology thanks to the recent appearance of the Holographic Planar Concentrator™ (HPC) designed by the American company Prism Solar Technologies, Inc. This is the key technology in Prism Solar products. The HPC acts as an extremely low-cost concentrator (3 suns) without mechanical tracking or cooling systems. The bifacial HPC configuration uses 72% less silicon than a standard module. This reduction in silicon along with other improvements has lowered the cost of a solar installation to below $1.00/W [120]. Furthermore, this new type of concentrator can be installed on rooftops or even incorporated into windows and glass doors.

3. Conclusions

A review of the available literature on concentrating systems which mainly cover the researches of the last 2 decades, from the point of view of building integration capabilities, has been presented.

High concentration systems optimize efficiencies in electrical production, by using multiple junction solar cells. When the aim is to combine production yields with building integration their characteristics become negative due to several aspects related to the need to incorporate them onto a high precision two-axis tracker and to move the entire system. Incorporation into buildings is best achieved on the roof of the building (particularly for flat roofs) where the system is invisible from the exterior.

Medium concentration systems can generally be divided into two groups: parabolic troughs and those using Fresnel optics in the form of lenses or mirrors.

The installation of parabolic trough concentrators in buildings is similar to that of high concentration systems; they are generally placed on flat roofs and are ideally hidden from view. Solar tracking is achieved by the rotation of the entire concentrator/receiver ensemble about a single axis.

Linear Fresnel reflectors offer a range of possibilities depending upon which technology they are based: two-axis tracking, tracking the sun by moving the mirrors or the PV receiver. Fresnel reflectors are able to work in a manner analogous to a lens, when the solar rays' trajectory is modified by reflection instead of refraction. In this way, optical losses are lower due to the high reflectivity of mirrors, in comparison to the transmissivity of Fresnel lenses. According to the incorporation into buildings, a good option is the system presented by the University of Lleida. In the device the receiver remains static and solar tracking is achieved in a simple and effective way by rotation of the individual mirrors. Thus overall movement is minimised facilitating incorporation into buildings and offering different possibilities for suiting the varied requirements of specific installations, leading to adequately fulfil requirements described in Section 1.

Linear Fresnel lenses, like Fresnel reflectors, satisfy expectations in terms of architectural integration. Fresnel lenses have in addition to the ability to separate the beam from the diffuse solar radiation makes them useful for illumination control in the building interior space. The Fresnel lenses are advantageous because they can combine within them both the concentrating element and the optically transparent window or cover in general.

In the low concentration systems group there are numerous variables of CPV generators, combining CPCs, planar reflectors, holographic films or fluorescent technologies with different technologies of solar cells (bifacial, thin films, etc.). The main characteristic common to all of them, moreover the low concentration ratio, is that they are static. This fact facilitates their placement at any location in buildings. It is necessary to remark that a higher concentration factor results in a higher cost reduction, and in this case usually it is around 2×. Fluorescent and holographic devices are capable of capturing higher fractions of the solar radiation than the rest of CPV and conventional PV systems.

Acknowledgement

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